Taguchi Robust Design Optimization for Water Cooled ISG Considering Temperature Distribution and Manufacturing Tolerance

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While mass production of electric motor is called for due to increase in application and demand, it causes discrepancy between design and product. This can affect the response of a motor. In particular, the tolerance of the shape or the residual flux density in the permanent magnet significantly affects the back electromotive force (EMF). When the magnitude of the back EMF changes, the current magnitude is changed to obtain the same torque varies. This consequently affects the loss of the motor, and hence leads to changes in efficiency. In particular, the changes in efficiency cause thermal problems for the motor such as irreversible demagnetization of the magnets and dielectric breakdown due to the increase in the temperature of the coils. Thus, despite the inevitable tolerance, the robust performances should be assure. In this paper, Taguchi robust design is applied to ISG motor by using the multi-response signal to noise for considering back EMF and coil temperature.

***Index Terms*—Control factor, integrated starter and generator, manufacturing tolerance, noise factor, Taguchi robust design, thermal equivalent circuit network**

I. Introduction

INTERIOR PERMANENT magnet synchronous motors (IPMSM) are widely used in residential and industrial applications, and in electric and hybrid vehicles, because of their high efficiency, high torque density, and wide speed range. However, even if a motor is designed using finite element analysis (FEA), its performance may not be satisfactory in certain cases. In addition to other factors, this could be due to the existence of manufacturing tolerance during the mass production of motors. This is because differences can occur in production even if factors such as the residual flux density, shapes of permanent magnets, and core size are designed as accurately as possible. Therefore, the response of the motor can differ from the design value. In particular, parameters such as the inductance and back electromotive force (back EMF) are closely related to changes in the linkage flux according to the manufacturing conditions for the permanent magnets, and these can affect the overall performance of the motor [1]. Furthermore, changes in the current due to parameter differences cause changes in the loss and temperatures of the permanent magnets and coils. Hence, dielectric breakdown in the coil and irreversible demagnetization of the permanent magnets can occur [2], [3]. Therefore, the temperature of the coils and permanent magnets should be verified using a thermal equivalent circuit network.

A robust design is essential to minimize the changes in response to the changes in the previously mentioned factors. In a robust design, the factors affecting the response are classified as control and noise factors, and the variation of the response is minimized by changing the controllable control factors with despite changes in the uncontrollable noise factors [5], [6]. Among the various robust design methodologies available, this paper used the Taguchi method to verify the temperatures of the permanent magnets and coils, as well as the back EMF, using a thermal equivalent circuit network and electromagnetic field analysis. Finally, an optimal robust model is obtained.

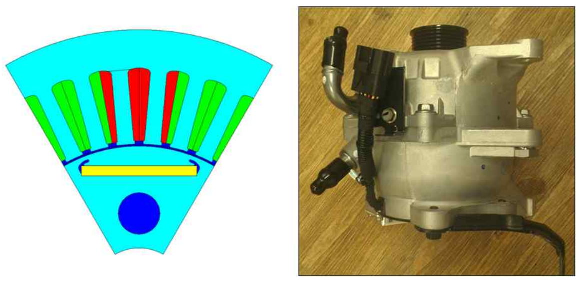


Fig. 1. The analysis model used to ISG.

II. Analysis Model

The analysis model is the 8kW IPMSM used to integrated starter and generator (ISG) in the automotive. Fig. 1 shows the analysis model and real model. The ISG is emerging as a low-cost fuel-saving technology in vehicles. In addition to its conventional alternator functions, it fulfills some functional requirements of mild hybrid systems, including starting the stopped internal combustion engine (ICE), driving the vehicle when starting, driving the auxiliaries when the ICE is stopped, and regenerative braking. Supporting the ICE during acceleration is also possible with ISG technology [4]. This motor is the proper type because the motor has wide speed range and water cooled operation which has sensitive temperature variation. Fig. 2 shows the test set for measuring the back EMF and temperatures.

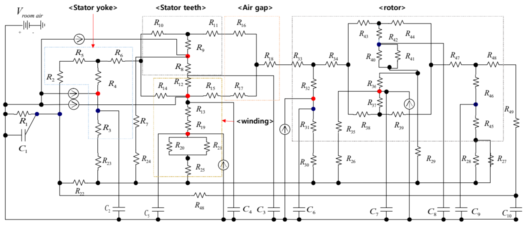


Fig. 2. Thermal equivalent circuit network.

III. THERMAL ANALYSIS

Various losses can occur in a motor, including copper loss, core loss, and mechanical loss. These losses can increase the internal temperature of the motor. Furthermore, such temperature changes vary because the rate of internal heat radiation varies according to changes in the shape. In particular, when a large increase in temperature is observed in the coils and permanent magnets, irreversible demagnetization occurs. Therefore, the temperatures of these parts must be specifically managed during the design. A thermal equivalent circuit network was used instead of computational fluid dynamics (CFD) to verify the temperature of each part of the motor quickly. A thermal equivalent circuit network was appropriate in this study because it made it possible to verify the temperature of a motor model under various conditions within a short period of time. Fig. 2 shows the thermal equivalent circuit network, and the equations related to each node can be expressed as follows

$$C_i \frac{dT_i}{dt} = \frac{1}{R_{ji}}(T_j - T_i) + g_i \tag{1}$$

where C_i is the i^{th} node thermal capacitance, T_i is the i^{th} node temperature, R_{ji} is thermal resistance between two adjacent nodes, i and j, and g_i is heat generation at node i. Fig. 3 (a) shows the test set, and (b), (c) is the back EMF and the temperature curve of a basic model.

IV. TAGUCHI ROBUST DESIGN

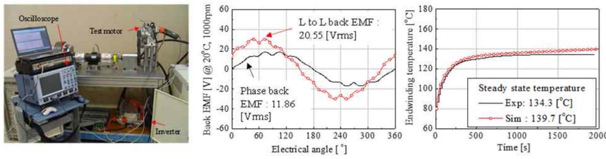
Fig. 4 shows the Taguchi robust design process with analyzing electrical and thermal performances as shown in Fig. 4. The temperatures of the permanent magnets and coils, and the back EMF, were set as the responses to ensure their robustness. And noise factors are listed in Table I. To consider electromagnetic and thermal characteristics simultaneously, multi-response signal to noise (MRSN) ratio is introduced. Quality loss functions of each performance are presented as (2) and (3) because the back EMF should be sufficiently large and the coil and permanent magnet temperatures should be small [7].

$$L_{ij} = k_1 \frac{1}{n_i} \sum_{k=1}^{n_i} y_{ijk}^2 \qquad \text{for the smaller – the - better response} \tag{2}$$

$$L_{ij} = k_2 \frac{1}{n_i} \sum_{k=1}^{n_i} \frac{1}{y_{ijk}^2} \qquad \text{for the larger – the - better response} \tag{3}$$

V. CONCLUSION AND REVIEW

The values of the coil temperature and back EMF changed according to seven factors defined in this study, and the details will be provided in the full paper. Furthermore, robust design technique can suggest the required direction during the motor design for mass production.



(a) (b) (c)

Fig. 3. Test set for measuring the back EMF and temperatures. (a) test set (b) back EMF analysis result (c) thermal analysis and test result

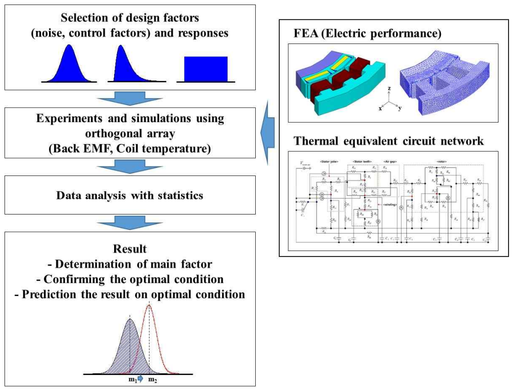


Fig. 4. Taguchi robust design process with analyzing electrical and thermal performances.

TABLE I
SELECTED NOISE FACTORS

No.	Noise Factor	Unit	Array Pattern 0	Array Pattern 1
1	Tolerance of PM (x)	mm	0.07	0.12
2	Tolerance of PM (y)	mm	0.07	0.12
3	Br value of PM(@100°C)	T	1.121	1.181

REFERENCES

[1] C. Choi, W. Lee, S. O. Kwon, and J. P. Hong, “Experimental Estimation of Inductance for Interior Permanent Magnet Synchronous Machine Considering Temperature Distribution,” *IEEE. Trans. on Magn.*,vol. 49, pp. 2990-2996, 2013.

[2] B. H. Lee, K. S. Kim, J. W. Jung, J. P. Hong and Y. K. Kim, “Temperature Estimation of IPMSM Using Thermal Equivalent Circuit,” *IEEE. Trans. on Magn.*,vol. 48, pp. 2949-2952, 2012.

[3] K. S. Kim, B. H. Lee, J. W. Jung and J. P. Hong, “Thermal Analysis of Water Cooled ISG Based on a Thermal Equivalent Circuit Network,” *J. Electr. Eng. Technol.*, vol. 9, pp. 893-898, 2014.

[4] S. J. Lee, K. S. Kim, S. Cho, J. Jang, T. Lee and J. P. Hong, “Optimal design of interior permanent magnet synchronous motor considering the manufacturing tolerances using Taguchi robust design,” *IET. Electr. Power Appl.*, vol. 8, pp. 23-28, 2014.

[5] A. Awada, B. Wefmann, I. Viering and A. Kleink, “Optimizing the radio network parameters of the long term evolution system using Taguchi’s method,” *IEEE Trans. Veh. Technol.*, vol. 60, pp. 3825-3839, 2011.

[6] G. Taguchi, Y. Yokoyama and Y. Wu, *Taguchi methods – design of experiments*, American Supplier Institute, Inc., 1983.

[7] M. A. Tsili, E. I. Amoiralis, A. G. Kladas and A. T. Souflaris, “Optimal design of multi-winding transformer using combined FEM, taguchi and stochastic-deterministic approach,” *IET. Electr. Power Appl.*, vol. 6, pp. 437-454, 2012.